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EFFICIENCY IMPROVEMENTS IN INDUSTRIAL ELECTRIC RESISTANCE FURNACES

Report No 90-13-K

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ABSTRACT

Factors affecting the efficiency of industrial electrical resistance furnaces are identified from published literature and discussions with furnace and insulation manufacturers. Potential improvements which could lead to enhanced energy efficiency and productivity are identified. Optimization of power requirements and insulation are among the most important improvements that could significantly enhance the efficiency of a furnace. Other factors identified include installation of monitoring equipment and electrical load shifting. A list of step-by-step check points is summarized to assist in analyzing existing industrial furnaces. Several projects with potential impact on the electrical efficiency of furnaces are also recommended.

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EXECUTIVE SUMMARY

Electrical resistance furnaces are among the most common electric heating technologies used in industrial applications. Their applications are numerous and they offer several advantages over other heating devices such as higher energy efficiency, improved environmental conditions and superior heating control.

Electric resistance furnace technology has been steadily improving. Advances were realized in power supply and control systems, heating elements and insulation technologies. The implementation of these new technologies should translate into improved energy efficiency and higher productivity of electric resistance furnaces. Yet, most of the industrial furnaces are far from optimized for high efficiency and productivity.

This study was initiated to examine the potential for efficiency improvements in industrial electric resistance furnaces. To achieve this objective, several tasks were undertaken. First, the important factors affecting furnace efficiency were analyzed. These factors include heat production, heat control, heat transfer, heat absorption and heat losses. This analysis was followed by a description of the types of furnaces used and possible applications for each type. Discussions with furnace and insulation manufacturers provided valuable information related to different aspects of electrical resistance furnaces. Among the areas discussed were: present technology, recent advances, economic assessments, user's concerns and requests, areas in which potential improvements could be most effective and possible R&D projects. The data were collected and analyzed to identify areas and methods for potential improvements and recommend R&D projects that could have potential impact on the efficiency of electric furnaces. As a result of this comprehensive analysis, a list of 20 'check-points' was summarized to serve as a quick reference for an easy step-by-step approach to analyze existing industrial furnaces. Several areas were identified in which potential improvements could lead to higher furnace efficiencies, improved productivity and/or lowering of operating costs. Some of these areas are optimization of power requirements, installation of adequate monitoring equipment, electrical load shifting and optimum type, thickness and design of insulation. R&D projects identified could be classified into three categories: electrical efficiency comparative tests, thermal efficiency comparative tests and specific analysis and recommendations for an industrial operating furnace.

In summary, this report provides a comprehensive analysis of factors affecting furnace efficiency and productivity and identify practical solutions to several problems. It is a useful guide which identifies modifications that could result in significant improvements in energy efficiency, in productivity and in reducing operating costs.

CHECK POINTS

1. Efficiency of power supply.
2. Energy consumption audit/analysis.
3. Defective wires, leads or contacts.
4. Use of optimum power.
5. Adequate monitoring equipment installed.
6. Possibility for heat focusing/concentration.
7. Use of continuous/PID power controls.
8. Operating furnaces during off-peak periods: load shifting.
9. Optimum configuration and activation control of elements.
10. Furnace operating near maximum element temperature.
11. Variations in type and size of load.
12. Types and properties of insulation.
13. Optimum thickness of insulation.
14. Type and size of refractory in support systems (cars, setters, saggars).
15. Tightly sealed doors and windows.
16. Gaps within insulation.
17. Defects and/or corrosion of insulation.
18. Application of high emissivity coatings.
19. Product and operational considerations.
20. Economic considerations and assessment.

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EFFICIENCY IMPROVEMENTS IN INDUSTRIAL ELECTRIC RESISTANCE FURNACES

1. INTRODUCTION

Applications of resistance furnaces in industry are numerous, and there is hardly an industrial sector that does not use them/1,2/. This is due primarily to the versatility, durability and reliability of such equipment, the ease with which it can be implemented, their maintainability, enhanced control and high efficiency.

Resistance furnaces are indirect heating devices, as opposed to conduction heating or resistance heating by direct current flow. The heating elements produce specific thermal energy (Q_T) which is then transferred to the object to be heated and to the walls of the furnace. The object absorbs a fraction of the energy dissipated by the elements (Q_C) but another part of the available energy constitutes thermal loss (Q_L). Improving the conditions for heat transfer and minimizing thermal losses will, in principle, result in higher furnace efficiency. This report examines the potential for efficiency improvements in electric resistance furnaces.

2. OBJECTIVES

The objectives of this project are to:

(a) analyze the factors affecting electrical furnace efficiency,

(b) discuss with furnace manufacturers recent advances in high temperature furnaces,

(c) identify areas in which potential improvements could result in enhanced furnace efficiency, and

(d) recommend specific research activities leading to practical/applied efficiency improvements in industrial electric resistance furnaces.

3. THE FURNACE

The furnace consists of a (heating) chamber heated by electrical resistances. The object to be heat treated is placed in the chamber which must be well insulated to minimize heat losses. The chamber is typically encased in a metal box. Electrical power supply and temperature regulation devices are also crucial parts of the furnace.

The study of furnace efficiency and the identification of potential improvements, therefore, involve analysis of the following: heat production; heat control; heat transfer; heat absorption; and heat losses. Details of this analysis, which are given in the Appendix, provide the background information on which the following discussion is based.

4. PRESENT ELECTRIC RESISTANCE FURNACES

4.1. Types:

High temperature electric resistance furnaces can be classified according to one of the following criteria:

furnace shape, eg. bell, chamber, tunnel;
direct or indirect radiation heating, eg. pot, muffle;
continuous, discontinuous or batch;
type of resistance elements, eg. metal coil or ribbon, SiC, $MoSi_2$, encased resistance;
motion of material within furnace, eg. vibrational, helical screw, continuous conveyor;
application, eg. heat treatment, melting, sintering.

Combinations of these criteria are numerous. The application is considered to be the most important criterion which actually determines the 'type' of furnace to be used. A list of the most common 'types' of electric resistance furnaces used in industrial applications is presented in the next segment.

4.2. Applications:

During the last twenty years, the use of electric heating in industrial applications has increased steadily, primarily due to instabilities in the fossil fuel prices and supplies. However, advances in the electric heating technologies during this period proved that there are other important benefits to be gained. High productivity, better process control and improved environmental conditions are among the most important advantages of the electric heating processes.

High temperature processes are at the heart of many industrial operations. Electrical resistance furnaces are among the most common electric heating technologies used in industrial applications/1,2/. Other electric heating technologies include induction, infrared and electric arc heating. The applications for electric resistance heating are too numerous to be covered in detail. Table I summarizes some of the most common applications and the type of furnace utilized in each application. Extensive details on the types of furnaces and their applications are available in published literature/1,2,3/.

TABLE I

TYPES OF ELECTRIC RESISTANCE HEATING FURNACES AND THEIR APPLICATION

FURNACE TYPE	APPLICATION							
	Metal Melting	Heat-Treatment Of Metals	Metal Heating	Firing	Bisque Firing	Glass Melting	Heat Treatment Of Glass	Brazing
Chamber		x		x	x		x	x
Bell		x		x	x			x
Tunnel				x	x		x	x
Crucible	x					x		
Basin	x	x	x					
Muffle		x						x
Fluidized Bed		x						
Continuous	x	x	x	x	x		x	
Discontinuous	x	x	x	x	x	x	x	x
Elevating	x							
Vibrational	x	x						
Conveyorized		x	x				x	
Pusher		x	x	x				
Fixed Hearth	x	x	x	x	x	x	x	x
Movable Hearth	x	x	x	x		x		
Vacuum		x	x					x

5. POTENTIAL FOR IMPROVEMENTS

The analysis and the discussions with furnace manufacturers, which are presented in the Appendix, provided an excellent basis for identifying several potential improvements in the design and operation of electric resistance furnaces. Most of these areas could lead to improvements in the efficiency of a furnace. Other important improvements in productivity and energy cost savings could also be deduced, and will therefore be identified and discussed. The points identified in this section can be used as a step-by-step approach to analyze the efficiency of existing industrial furnaces and, subsequently, identify action items to improve any existing deficiencies. To simplify this step-by-step approach, a list of 'check points' is given.

In order to identify potential improvements in furnaces, their efficiency must be clearly assessed and analyzed. The efficiency of a furnace (η) depends on its electrical efficiency (η_E), its thermal efficiency (η_T) and their variation with time. Each of these is discussed in the following sections.

5.1. Electrical Efficiency Improvements:

Electrical efficiency (η_E) can be expressed as the ratio of the electrical energy converted into thermal energy (Q_T) to the electrical energy supplied to the furnace (Q_E); ie,

$$\eta_E = Q_T / Q_E \qquad [1]$$

Electrical energy losses ($[Q_E - Q_T]/Q_E$) are usually less than 5%/4/. Large deviations from this figure suggest either defective elements, leads and/or contacts or the use of an out-dated electrical/electronic technology. In either case, corrective measures must be applied. If these defects are not rectified immediately, not only will the electric efficiency drop, but damage to the elements, leads and insulation is likely to occur. Also, as a result of overheating, the defective furnace may present a fire hazard.

In the next segments, the various aspects that could result in improving the electrical efficiency of electrical resistance furnaces are discussed.

5.1.1. Power Requirements:

In simple terms, the power requirement for a given process is determined from the following equation

$$W_P = \frac{Q_C + Q_W}{t} + W_L \qquad [2]$$

where: Q_C is the energy required to raise the temperature of the charge in a time t,
Q_W is the heat energy accumulated/lost in the furnace walls during the heat-up process, and
W_L represents the thermal losses at the final temperature.

Also, the size and relative position of the load to the elements as well as the elements' relative position to each other and to the furnace walls, all play an important role in the radiation heat transfer between the elements, the walls and the load. The Stefan-Boltzman law of radiation (equation [A10]) takes into account all of these parameters. Therefore, an accurate analysis of the physical and thermal properties of the load, the insulating materials and the elements is required for the determination of the optimum power requirements. In practice, the installed power is larger than the calculated value. Also, because the resistance of the elements is expected to increase with age, a reserve voltage, up to 100% of the original voltage requirement, is usually recommended/5/. The value of the reserve voltage depends on the aging characteristics of the elements used. A variable voltage power supply is usually used to control and change the power requirements.

For manually controlled furnaces, optimum power requirements for each type of product/load should be accurately determined. The use of less than optimum power will result in inadequate heating of the load. The (under heating) results are usually clear to the manufacturer and the corrective measure is apparently simple: increase the power. On the other hand, the use of greater than optimum power will result in a higher operating temperature. The effect of over heating on the final product is usually not critical or noticable to the manufacturer. However, the electrical energy used to raise the load temperature over the optimum value (over heating) is wasted energy, and the efficiency of the furnace will suffer. Several tests must be undertaken by manufacturers, for each manually controlled furnace used, to determine the optimum power requirement for each type of product/load. The installation of power/temperature controls onto these furnaces is a better solution to effectively optimize the power utilization (see Section 5.1.4. and Appendix, Section 2).

5.1.2. Monitoring Equipment:

In order to have a continuous and accurate evaluation of the energy consumption for a particular process and furnace, monitoring equipment is required.

Energy consumption as a function of load type and quantity must be periodically tabulated. Total resistance of heating elements, leads and contacts must also be checked periodically. Monitoring the temperatures of the load as well as the inner and outer walls of the furnace is also required. Furnace linings must be periodically inspected and tested for corrosion, deterioration and gaps. Comparisons with manufacturer operating reference parameters or other reference values obtained under optimal operating conditions should be undertaken.

Deviations from reference parameters should be addressed sooner rather than later. It is easier to identify and isolate one cause of inefficiency before other factors also start to have significant effects on the efficiency of the furnace.

5.1.3. Heat Focusing:

In some industries, such as the glass and metal sheet industries, only localized heating of the load is required. Bending of metal and glass sheets is one typical application for localized heating. In practice, however, the entire load is heated mainly to prevent thermal stresses that would have arisen if localized heating was used.

Advances in material science and computer modelling and analysis could be useful in solving this difficulty. A detailed temperature field and thermal stress distribution could be easily determined for a certain type of material under specified heating conditions. The number and location of the heating elements, relative to the load and to each other, could be analyzed to obtain the optimum heat distribution that would prevent damage of the material due to localized heating. Material properties could also be modified (usually without any significant effect on end use function) to further reduce thermal stresses.

The focusing of the heat on the sheets (or other loads) will translate into using a smaller number of heating elements and significant reductions in energy consumption.

5.1.4. Power Control:

In contrast to discontinuous (on/off) control, continuous/PID[1] control systems provide smooth and precise heating curves. The use of these controls will not improve the electric efficiency of the furnace but will permit the use of higher power density elements, continuously, at their maximum temperature. Several advantages will be gained by installing a PID control system. Firstly, increased productivity, since the rate of temperature increase to operating temperature is faster than conventional (on/off) controls and the furnace could be operated at the maximum operating temperature (equation [A10]). Secondly, if operating temperature is below the maximum temperature of the elements, the power (load) demand for the furnace could be reduced (equations [A10] and [A11]); this would also translate into additional savings in energy costs since electricity charges for many manufacturers are based on the peak-load (kW) as well as the consumption (kWh). Thirdly, by lowering the operating temperature the service life of the elements is increased and the stable temperatures throughout the heating cycle may allow the use of low cost elements. Fourthly, excellent temperature accuracy is achieved which may improve the quality of the product.

5.1.5. Load Shifting:

Another advantage of installing continuous power control to a furnace is its added ability for electrical load shifting.

For discontinuous furnaces, the operating furnace temperature could be attained during off-peak hours. This is the heating zone that usually requires maximum electrical power. (The use of low thermal mass insulation will certainly help in achieving the heat-up process during off-peak periods.) Once the operating (eg, holding/melting) temperature is reached, the power requirement for a given process decreases (see Figure A3). This load shifting procedure will benefit both the utility and the consumer. Reducing the electrical load during periods of peak demand and utilizing (unused/excess/wasted) electrical energy during off-peak hours are important aspects of the utility's demand management. Industrial customers will benefit from the reduced energy costs by operating during off-peak periods and lowering the peak-load during regular operating hours.

5.2. Thermal Efficiency Improvements:

The thermal efficiency of a furnace (η_T) could also be expressed in a similar manner as its electrical efficiency (η_E), ie,

$$\eta_T = Q_C/Q_T \qquad [3]$$

where Q_C is the thermal energy stored in the load at the end of the thermal operation (as defined in equation [2]). The difference $Q_T - Q_C$ represents furnace losses.

Thermal efficiency is generally used as a measure of furnace characteristics or performance. In the next few segments a discussion of some possible techniques for improving the thermal efficiency of furnaces is presented.

5.2.1. Insulating Materials:

Indeed, the insulating material of a furnace is the most important factor affecting its thermal efficiency. Thermal insulation absorbs a significant amount of the thermal energy produced by the heating elements. In many cases, this amount exceeds that absorbed by the load, thus reducing the thermal efficiency to below 50%. Also, depending on the design and type of insulation, an additional amount

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[1]PID refers to Proportional, Integral and Differential control systems which are often employed as continuous control. For a more complete discussion of controls refer to the Appendix, Section 2.

of energy escapes through the furnace walls. Thermal losses through the walls increase with increased temperature of the outside shell of the furnace (radiation equation [A10] and Figure 1a). For example, for a 5°C difference in the outside wall temperature, say between 75 and 70°C, the thermal loss increases by about 13%. A simple and obvious solution to this problem is to increase the thickness of the insulation to reduce the outside shell temperature. This will increase the accumulated energy in the insulation, thereby reducing its final effect on improving the thermal efficiency of the furnace.

Therefore, for a particular type of insulation, an optimum insulation thickness must be determined. Figure 2 explains how the optimum thickness of a furnace wall is determined. In simple terms, the optimum wall thickness is that thickness at which the sum of the thermal losses is minimum.

As discussed in the Appendix (Section 5. Heat Losses), fibre insulation materials offer significant advantages over the traditional brick insulation. In particular, their lower density and thermal conductivity will provide superior insulation with lower mass; ie, thermal losses and energy stored in the walls will be reduced, thus allowing the thermal efficiency to be increased significantly (equation [1]). High temperature furnace users should seriously consider the replacement of existing high density refractories with fibrous insulation. A wide variety of these materials currently exist to satisfy the different requirements of the furnace users. Fibre insulation with high mechanical strength and resistance to various corrosive environments are now readily available in the marketplace. Furnace users must carefully assess the cost, the impact and payback of the replacement. Furnace manufacturers, supported by extensive practical and theoretical evidence (see, for example, Figure A6), appear to be confident that payback periods are very short.

A second application for the low mass refractories is its use in kiln cars, setters, saggars, etc. Industries such as the electrical porcelain, sanitaryware, dinnerware, brick and clay, tile and electronics can all use the various types of low thermal mass refractories in the different support systems. Kiln furniture manufacturers claim that mass reductions between 25 - 50% are possible. The reduction in the total mass of kiln insulation and cars could result in energy savings of about 40% and an increase in productivity of about 26%/6/.

5.2.2. Design Aspects Of Insulation:

Improvements in the design of the complete insulation system of a furnace could result in additional enhancement of its energy efficiency.

Heat leakage through furnace doors, which are not tightly sealed or opened for prolonged periods, is a common source of furnace inefficiency. From Figure 1b, the amount of energy lost for any opening can be calculated. For example, if an opening around a door of a furnace operating at 1200°C is 2 m long and 1 cm wide, then the heat lost through this opening is about 5 kWh/h. This suggests that if the door gap is eliminated through proper design, the furnace load could be reduced by 5 kW and still provide the thermal energy required to heat the load. In addition to energy and cost savings, higher quality products are most often produced due to the reduction in oxidation caused by the ingress of cold air. Similarly, for doors that are opened for prolonged periods of time, alternate designs or modifications must be carefully considered and assessed to reduce heat losses. Some suggestions for reducing heat losses through doors include: the installation of power devices on doors to reduce the time the doors are open; minimize the size of the door; and whenever applicable, use smaller openings to fill and/or empty the furnace contents.

Consideration must also be directed towards the arrangement of the insulation lining inside the furnace. A checkered pattern is recommended to replace the common parallel pattern. This arrangement will eliminate the usual separation of the joints, of the insulation blocks, due to shrinkage. For the same reason, composite layers of insulation should be staggered.

Other important aspects of insulation design to be considered are the type of materials in a composite insulation lining, corrosion resistance to furnace atmosphere and adequate mechanical strength and integrity at high temperatures. Poor designs that do not account for these factors will result in insulation failure thus lowering the efficiency of the furnace and increasing the cost of repair. In addition, the cost of different insulation alternatives must be compared and analyzed in terms of life expectancy, energy efficiency and pay back periods.

5.2.3. Heat Transfer Improvements:

Convective heat transfer does not play a significant role in the heat transfer of furnaces operating at temperatures above 750°C. In such applications, only minor improvements in the temperature uniformity within a furnace could occur using forced convection.

Heat transfer by conduction controls the rate of heating of the load and of the insulation (equations [A7] - [A9]). The effect of thermal conductivity on performance of insulating materials was discussed earlier (V.2.i). As for the load to be heated, its thermal conductivity, in most cases, is a parameter that furnace users would likely not vary. Therefore, before replacing high thermal mass insulation by low thermal mass insulation, a careful analysis of the effect of possible changes in the heating rate of the load must be undertaken. In any event, changes in the thermal conductivity of the load will not have any significant effect on the efficiency of a furnace.

More significant thermal efficiency improvements can be achieved through improving the radiation heat transfer mechanisms within a furnace. In theory, if the heat transfer between the elements and the load is improved/maximized, this translates into optimum performance of furnace and reduces thermal losses (W_L) and energy stored in the insulation (Q_w). The power requirements for such a furnace will then be reduced (equation [2]).

A careful analysis of the radiation law equation [A10] suggests that the specific power derived from the elements depends on two factors: the temperature difference between the load and the elements and the global form factor. The former parameter is by far the most important in improving the performance of a furnace. For example, at a constant global form factor (= 0.4, say), and a load temperature of 900°C, the surface power emitted from an element at temperatures 1050, 1100 and 1150°C will be 2.7, 3.8 and 5.1 W/cm^2, respectively. This example indicates that a reasonable increase in the elements operating temperature (in this case, 14%), will result in increasing the power density of the elements by 89%. On the other hand, only modest increases in the global form factor are practically possible, which in turn will have small effects on the performance of the furnace (ie, increasing the specific power of elements).

Heat transfer mechanisms could also be optimized to improve the thermal efficiency of a furnace. The basic concept is to minimize the thermal energy escaping the furnace. One possible technique is to minimize the energy penetrating the insulation by reflecting it back onto the load. At the present time, this approach is not economical since only noble metal (gold or platinum) foils or coatings could be used for high temperature furnace applications. Also, efficiency improvements, of about 10%, resulting from the application of high reflectivity linings occur only during the heating-up periods. During holding periods, the energy efficiency of a furnace lined with high reflecting material will approach that of conventionally insulated furnaces. High reflectivity coatings based on less expensive metal oxides, are still in the developmental stage/7/.

A second approach to minimize the energy penetrating the insulation is by coating it with a high emissivity lining. When the coated insulation absorbs heat from the elements, it will become hot and will emit (secondary) radiation back to the load. In fact, the applied coating could also act as a partial reflector to the incident energy. Application of high emissivity coatings were reported to have increased the emissivity of the insulating materials by factors up to 5 times/8,9/. In general, the emissivities of coated insulation is in the range 0.80 to 0.92. The uncoated insulating materials have

emissivities in the range 0.2 to 0.6. When the insulation lining becomes hot, and warmer than the load, because of its close proximity to the elements, it acts as a heat emitter. The simplified global form factor equation [A11] suggests that increasing the emissivity of the surface of the insulation will result in increasing the re-emitted heat flux by about the same factor. This will result in reducing the amount of energy penetrating through the insulation thereby increasing the efficiency of the furnace. Improvements in energy efficiency up to 40% and reduction in heat-up times of about 30% have been reported/10/. On average, efficiency improvements of about 25% are to be expected/8,10,11/. In addition to its favourable effect on efficiency and rapid heating, high emissivity coatings proved to enhance uniformity of heating within a furnace, eliminate the refractory/fibre dust and increase the service life of insulation linings. Different types of high emissivity coatings are currently available; they could be easily applied to most types of existing insulation and can be used in any heating application. The cost of the coatings is about $25 per square foot. Cost recovery would therefore be possible within a reasonable time period.

Additional improvements in heat transfer could be realized by optimizing the positions and shape of the heating elements relative to the location and size of the load (thereby increasing the global form factor). Controlling the activation of a particular set and number of elements (ie, sequencing) within a furnace would provide an added flexibility to the furnace, in particular when different types and sizes of loads are to be heated. This procedure will reduce energy consumption and the average power demand of the furnace.

5.3. 20 Check Points:

Based on the discussion presented above, a list of 'check points' summarizing a step-by-step approach is given. This quick reference could be easily used to analyze existing (operating) furnaces particularly in the areas of energy efficiency and productivity. For convenience, an index/reference is provided for detailed explanation and discussion of the points outlined.

CHECK POINT	REFERENCE IN REPORT Page Number
1. Efficiency of power supply.	4, 5
2. Energy consumption audit/analysis.	4, 5
3. Defective wires, leads or contacts.	4
4. Use of optimum power.	4, 5, 27, 28
5. Adequate monitoring equipment installed.	5
6. Possibility for heat focusing/concentration.	5
7. Use of continuous/PID power controls.	5, 6, 24, 25
8. Operating furnaces during off-peak periods: load shifting.	6
9. Optimum configuration and sequencing of elements.	11
10. Furnace operating near maximum element temperature.	10
11. Variations in type and size of load.	5
12. Types and properties of insulation.	6, 7, 30
13. Optimum thickness of insulation.	7
14. Type and size of refractory in support systems (cars, setters, saggars).	6, 7, 30
15. Tightly sealed doors and windows.	7
16. Gaps within insulation.	7
17. Defects and/or corrosion of insulation.	7
18. Application of high emissivity coatings.	10
19. Product and operational considerations.	6, 8, 24, 28, 29
20. Economic considerations and assessment.	7, 11, 24

Areas in which potential improvements are possible could be easily identified. All possible solutions and alternatives should then be outlined. A cost analysis and investment recovery period should also be discussed in detail. Usually, the cost/recovery element is the most significant factor as viewed by furnace users. Finally, a plan for implementing the acceptable improvements should be worked out together with the furnace user.

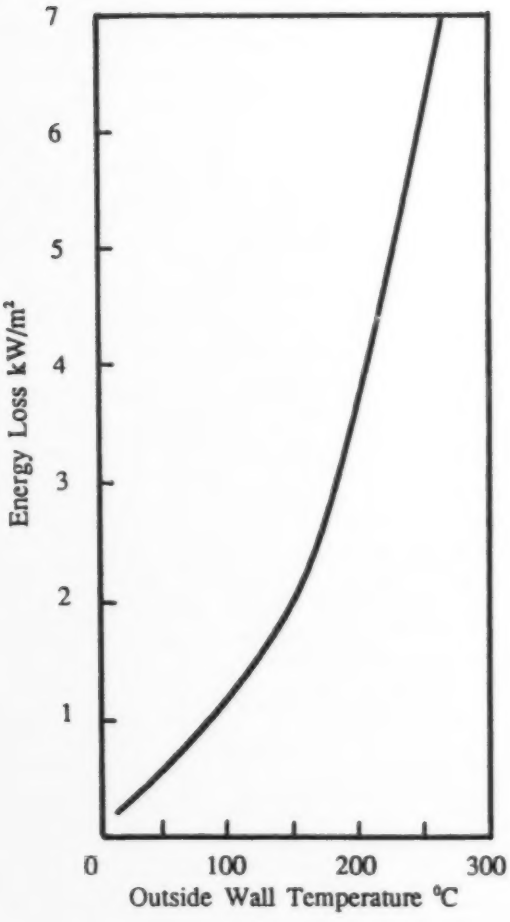

FIGURE 1a
Energy Loss From Walls

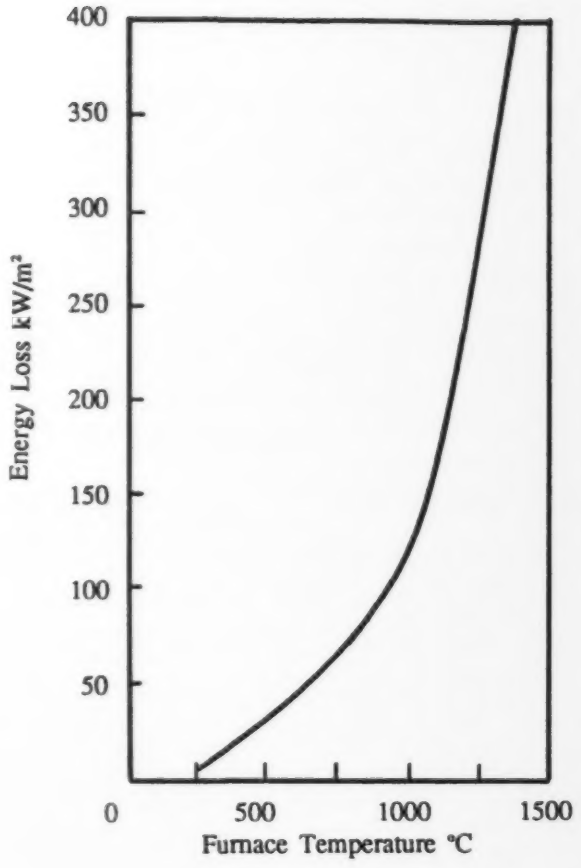

FIGURE 1b
Energy Loss By Radiation Through Openings

FIGURE 1

Energy Losses From Furnaces

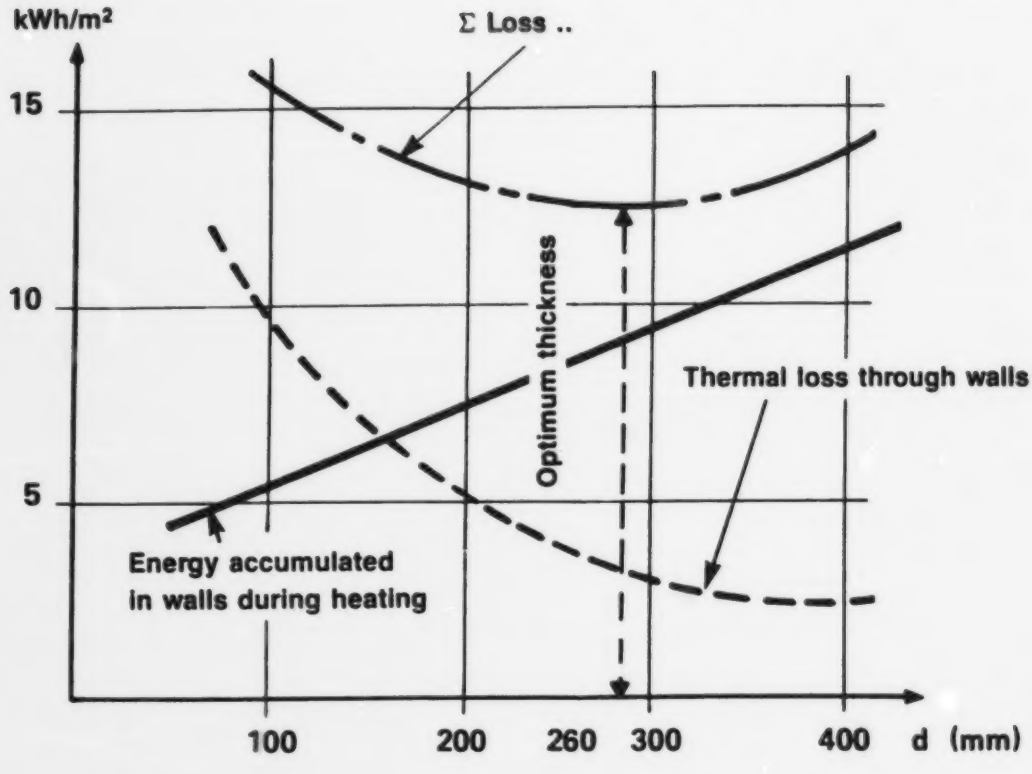

FIGURE 2

Determination Of Optimum Insulation Thickness

6. CONCLUSIONS

From the analysis/discussion presented above and in the Appendix, the following conclusions can be drawn:

1. A wide variety of electric resistance furnaces are currently being used in numerous applications. Due to advances in electric resistance furnace technology and advantages over other heating furnaces, the use of electric resistance furnaces in industrial processes is steadily increasing.

2. The efficiency of a furnace can be divided into two main aspects: electrical and thermal efficiency.

3. The electrical efficiency of a furnace should be about 95%. Furnaces with electrical efficiencies below this value imply either defective components or an older type of electrical power supply, regulator, transformer and/or controls.

4. Although the margin for improving electric efficiency is small, the implementation of several suggestions, if they were not already in place, will result in further improvements in the electrical efficiency of furnaces. These suggestions are related to using optimum electric power, installing monitoring equipment and heat focusing.

5. Productivity enhancement and lower energy costs could be realized by adopting continuous/PID power controls and load shifting respectively.

6. Thermal efficiencies of furnaces are typically about 55%. Therefore, the potential for efficiency improvements in this area is significant.

7. Improvements in the various aspects of thermal insulation of furnaces could easily enhance their thermal efficiency. The most important task is the installment of low thermal mass insulation with optimum thickness. The expected result is an efficiency improvement of 10 to 40 %.

8. Reducing heat leakage, minimizing door openings and arrangement of insulating linings of a furnace are among the design improvements that could also be undertaken to increase the thermal efficiency of furnaces.

9. At temperatures above 750°C, heat is mainly transferred by radiation. Heat transfer improvements will result in increased efficiency as well as increased productivity of furnaces. Thermal efficiency improvements of about 25% are expected from the application of high emmissivity coatings to the inner insulating lining of furnaces.

10. The high cost of low thermal mass insulation and high emmissivity coatings deters furnace users and manufacturers from using them.

7. RECOMMENDATIONS FOR FUTURE WORK

Advances in technology and its practical/industrial implementation were always preceded by progress in research and development (R&D). Industries are most often reluctant to implement new technologies unless they are backed by extensive R&D evidence of their techno-economic effectiveness. Many furnace manufacturers and users do not have the R&D capabilities to develop new products and/or techniques or to examine and test new products which could be effective in improving the performance and efficiency of their furnaces. Independent and unbiased analysis and tests, under practical conditions, are usually required before furnace users and manufacturers modify existing furnaces.

As a result of this analysis and discussions with various manufacturers, projects that could have potential impact on the electrical efficiency of furnaces are identified. The future work recommended here could be undertaken by Ontario Hydro's Research Division, Energy Management Division, Regions and/or external consultants and manufacturers. The results of these projects are expected to benefit furnace manufacturers and users as well as electric supply authorities.

7.1. Electric Efficiency Comparative Analysis:

Although the electrical efficiency (η_E) of most resistance heating furnaces is high, and therefore the impact of any R&D projects in this field is expected to be small, the sum of electric efficiency improvements, each of the order of 1%, is still considered beneficial. In addition, some cases where older furnace power supplies are used, the benefits could be significant. The following projects are suggested in the electric efficiency area:

1. Gather information and assess techniques to measure the electrical efficiency of furnaces. Based on this study, simple procedures should be established to undertake electrical efficiency measurements on industrial furnaces.

2. Compare the efficiency specifications of furnace power supply systems available in the market-place. Power supplies could be classified by one or a combination of their specifications such as output power range, current delivering capacity and number of phases. Collect data on samples of power supply systems presently installed. Compare efficiency specifications provided by furnace manufacturers to the actual field efficiency. Analyze the results and discuss with furnace manufacturer(s) and user(s).

3. Analyze the components and functions of (at least) two furnace power supply systems: one of the most efficient systems, and another with a lower electric efficiency (determined from project 1 above). Identify areas of possible improvements for both systems with particular emphasis on the lower efficiency one. Actual testing of the electric efficiency of these systems could also be undertaken as part of the project.

4. Compare the effectiveness of on/off and continuous/PID controls on the performance of a furnace. Although electric energy efficiency should not differ in both cases, the results and analysis of this exercise should have interesting and useful implications, especially in relation to increasing thermal efficiency, productivity, load shifting, elements' service life and quality of product.

5. Identify and classify the electric resistance furnaces installed and used in Ontario. Although this might not be classified as an R&D program, the data compiled in this project will permit a more systematic, focused and effective approach for improving the efficiency of installed electric resistance furnaces. Classification of industrial furnaces could be based on industry/application, type of furnace, maximum power and/or energy consumption.

7.2. Thermal Efficiency Comparative Tests:

Compared to electric efficiency improvements, this is an area where R&D projects could result in significant improvements in the energy efficiency of electric resistance furnaces. The following is a summary of R&D projects identified in this area.

1. **Prototype of high efficiency furnace.** The information gathered from all tests and various analysis and data collected could be effectively used to design a high efficiency electric resistance furnace. Additional variables that have to be examined are: relative positions of the elements and their size, power control system(s), and design of furnace insulation. The prototype is then tested for efficiency and the results compared to other furnace efficiencies. A cost analysis is to be prepared as well.

The prototype furnace could also be used to undertake in situ tests on the efficiency of various classes of insulation material (eg, brick, alumina fibers, zirconia fibers, etc.).

2. **High emissivity coatings, analysis and tests.** Identify the high emissivity coatings available for high temperature furnace applications and collect all relevant data on these coatings. Using one type of refractory lining in a furnace, and one load, determine the effect of the various coatings on the efficiency of the furnace. The results are to be compared with efficiencies of the same furnace before the application of coatings. The scope of this project can be widened by determining the efficiency of the furnace when different coatings are applied to different insulation linings. These tests could also be incorporated as an additional part of the previous project.

3. **Testing and characterizing insulating materials.** The wide variety of available insulating materials makes it very difficult for furnace manufacturers to have an independent assessment on all, or most, of them. Technical data provided by refractory manufacturers are usually derived under ideal or special experimental conditions. In most cases the data are not complete, and in some cases ambiguous. Manufacturers arbitrarily select materials that appear to have some of the required criteria. Compromises are very common.

The purpose of this program is to test and characterize about three classes of insulating materials that cover a wide range of critical properties. Tests will include density, melting point, maximum operating temperature, thermal conductivity, specific heat, strength, corrosion resistance to specific environments and electrical resistance. Two sets of tests should be undertaken as a function of temperature, up to the maximum operating temperature. In one set, properties are determined under uniform temperature conditions throughout the volume of the material being tested, ie, equilibrium conditions. The second set of tests should be undertaken with one side of the insulation warmer than the other, ie, similar to temperature profiles inside an operating furnace. All data should then be analyzed, tabulated and graphed. The results are to be compared to the technical data available for each refractory tested.

Due to the complexity of this project, it can be divided into many smaller projects, each addressing only one property. However, the complete set of properties must eventually be compiled in a comprehensive data base to have maximum benefit.

4. **Aging characteristics of insulation.** Under actual operating conditions, insulation characteristics will undoubtedly change. For example, the burn-off of binder from the insulation will gradually occur as soon as the furnace heats up. Shrinkage will occur as a result. This will be compounded by additional shrinkage due to heat cycling. Other important parameters that change as a result of aging are the chemical composition and density of the refractory. These, in turn will affect other critical properties such as thermal conductivity, mechanical strength and corrosion resistance. The users have no choice but to keep operating the furnace under conditions far from optimum when and if these changes occur. Usually this translates into inefficient furnaces.

After identifying one or two main furnace applications (from project (4) of the Electrical Efficiency Comparative Tests), aging characteristics of the most suitable insulating materials for the particular

application should be undertaken. The most suitable insulation could be identified by furnace users, manufacturers or from project (1) or (4) of the Thermal Efficiency Comparative Tests. Aging characteristics should include most of the relevant properties.

7.3. Specific Detailed Analysis and Application:

A company using electric resistance furnaces is to be identified to examine, analyze and modify one of its operating furnaces. In order to benefit as many electric furnace users as possible, this project should be undertaken on a type of furnace that is common to many industrial sectors. This could be determined from the data collected in project (4) of the Electric Efficiency Comparative Tests.

The tasks of this project should include: furnace analysis using the '20 Check Points'; identify solutions and alternatives; prepare a cost analysis and investment recovery possibilities; discuss options with manufacturer; outline with manufacturer an implementation plan; modify the furnace; undertake pre-operation tests; initial determination of efficiency for modified furnace; monthly auditing of furnace performance and efficiency monitoring for one year.

VII.4. Other Projects:

In addition to the work suggested, other projects could be undertaken that could also translate into enhanced furnace efficiency. Among these projects are: (i) education programs that would increase the awareness of furnace manufacturers and users of the latest advances in electrical furnace components -this could be in the form of brochures, seminars or direct personnel contacts; (ii) workshops with users and manufacturers of industrial electric resistance furnaces to discuss practical difficulties and potential for improvements; (iii) an awareness campaign of the various EMC (Energy Management Challenge) and other Ontario Hydro incentive programs related to electrical furnace efficiency and load reduction.

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APPENDIX

1. HEAT PRODUCTION

Resistance heating is the conversion of electrical energy to thermal energy as an electrical current passes through a resistor. The electrical properties of the resistor obey Ohm's law:

$$V = RI \qquad [A1]$$

where: V is the potential difference across the resistor (volts),
R is its resistance (ohms), and
I is the current flowing through the resistor (amperes).

The electric power (W) is the work done or heat generated by the electric current per unit time (watts). It is expressed by the following equation:

$$W = VI = RI^2 = V^2 / R \qquad [A2]$$

The electric energy (Q_T, joules) converted into heat in a total time t (seconds), is given by:

$$Q_T = Wt = VIt = RI^2t \qquad [A3]$$

In industrial applications, energy is generally expressed in kilowatt hour (kWh), representing the energy dissipated in one hour by a resistor absorbing a constant power of 1 kW (1 kWh = 3600 kJ).

The power (W_P) requirements for a furnace are determined using the general expression:

$$W_P = \frac{Q_C + Q_W}{t} + W_L \qquad [A4]$$

where: Q_C is the energy required to raise the temperature of the charge in a time t,
Q_W is the heat energy accumulated/lost in the furnace walls during the heat-up process, and
W_L represents the thermal losses at the final temperature

At the heart of the resistance heating technology are the resistance heating elements. Heat is produced by these elements. There are two basic types of resistance heating elements: metallic and non-metallic. Metallic (usually alloys) resistors are most commonly used for heating applications below 1200°C while non-metallic elements are used when temperatures up to 1750°C are required. For higher temperatures, special elements such as tantalum, tungsten or zirconia are used. Table I gives some examples of each category and some of the relevant properties of each resistor material.

Element selection is fundamental in optimizing heating processes, as well as the capital and operating costs of a furnace. There are a number of factors that must be considered in selecting the heating elements:

1.1. Operating Temperature:

Since the maximum temperature attainable in a furnace depends on the maximum operating temperature of the elements, this is the first characteristic to be considered in choosing a resistance element. To prevent damage to the elements and increase their service life, the furnace's operating temperature must be lower than the softening temperature of the element's material (and most certainly much lower than its melting point). As shown in Table AI, operating temperatures higher than 2000°C can be achieved with current heating element technology. Such high operating temperatures provide new avenues for novel industrial processes and products.

1.2. Power Density:

This factor gives the amount of power that a unit area of an element can deliver to the furnace walls (and load) at a given operating temperature (W/cm^2). High power densities are desirable in order to reduce heat-up time and therefore increase productivity in an industrial heating process. For a given type of element, the power density decreases with increasing operating temperature The power density of an element is also dependent on the ambient atmosphere of the furnace; it is lower when atmospheres other than air are used. Table AII compares the power density at different temperatures for several common heating elements. Clearly, non-metal elements could provide larger power densities than metallic ones. However, other factors such as cost, product demand and nature of load are to be considered, and an optimum must be determined between costs and gains of using a given type of heating element.

1.3. Electrical Resistivity:

The electrical resistivity of a heating element controls the heat energy produced in a furnace as well as the electric power requirements for a furnace (relations [A2] and [A3]). The resistance R (ohms) of a heating element of length d (cm), uniform cross-section S (cm^2) and resistivity ρ (ohm.cm) is given by:

$$R = \rho \, d / S \qquad [A5]$$

The electrical resistivity is a characteristic property of each material (or compound). Resistivity varies with temperature according to the expression:

$$\rho_T = \rho_o (1 + \alpha T) \qquad [A6]$$

where: ρ_T is the resistivity (ohm.cm) at temperature T (°C)
ρ_o is the resistivity (ohm.cm) at 0°C
α is the resistivity temperature coefficient ($°C^{-1}$)

The use of materials with relatively high resistivity allows a reduction in the length of the element (equation [A5]). Also, for constant power and fixed dimensions, the use of high resistivity material limits the electric current (relation [A2]).

The value of the temperature coefficient of resistivity α, should be low, positive and more or less constant over the furnace operating range. A low and nearly constant α dispense with the requirement for expensive regulating and starting devices. On the other hand, the positive temperature coefficient allows the dissipated power to regulate itself, especially in the event of an accidental increase in temperature.

TABLE AI

PROPERTIES OF COMMON HEATING ELEMENTS

TYPE/COMPOSITION OF ELEMENT	MAX. OPERATING TEMP.(°C)	POWER DENSITY AT 1000°C(W/cm²)	RESISTIVITY AT 20°C (.cm)	TEMP.COEFF. OF RESIST.(10^{-6}/°C)	EXPANSION COEFF. 10^{-6}/°C
I. METALLIC					
Iron-Nickel-Chromium Fe-Ni60-Cr23	1150	1.1	112	158	17.8
Nickel-Chromium Ni70-Cr30	1250	1.5	118	58	17.5
Iron-Chromium-Aluminum Fe-Cr22-Al15.5	1375	4.0	145	40	
Platinum-Rhodium Pt-Rh20	1700	2.0	21	12100	
Tantalum Ta	2400(Vac/Inert)	15	13	3000	
Tungsten W	2800(Vac/Inert)	15	6	5500	
II. NON-METALLIC					
Molybdenum Disilicide $MoSi_2$	1800	8.0	35	5500	7.5
Lanthanum Chromite CrO-LaO	1850		$20x10^6$	14	
Zirconia ZrO_2	2200				
Carbon Synthetic Graphite	2600(Vacuum)		900	-400 (0-500°C) +360 (500-1200°C)	
Silicon Carbide SiC	1550	25	$0.2x10^6$	-880 (0-650°C) +400 (650-1600°C)	

TABLE AII

EFFECT OF TEMPERATURE ON POWER DENSITY OF HEATING ELEMENTS

ELEMENT TYPE	POWER DENSITY (W/cm^2)				
	800°C	1000°C	1100°C	1300°C	1500°C
Fe-Ni60-Cr23	2.0	1.1	0.5		
Ni70-Cr30	2.4	1.5	0.85		
Fe-Cr22-Al15.5		4.0	3.0	1.5	
$MoSi_2$		8.4	7.3	6.0	5.0
SiC			25	14	<1

The change of resistance with time and usage is also a very important factor. As a result of surface oxidation, the resistance of an element generally increases with time and use (ie, aging). Changes in element(s) resistance in a furnace will alter the dissipated power and maximum operating temperature (both usually decrease), disrupt the control system and complicate the process of replacing old elements by new ones.

Connecting resistors in different ways also considerably affects the power dissipated. For example, two resistors connected in series would provide one-quarter of the dissipated power of the same two resistors connected in parallel (at a constant voltage); also, three resistors connected in a star form will provide one-third of the dissipated power if the three resistors were connected in a delta shape. Selector switches are often used to control the furnace power by changing from one type of configuration to the other during a heating process. Recently, however, electronic and continuous power modulation systems are rapidly replacing this type of resistance power variation system.

1.4. Mechanical Strength:

The heating element (system) must be mechanically strong at all operating temperatures. The resistance element must be uniform and must maintain its structural integrity up to the maximum operating temperature. Also, the strength of the element must not decrease with time. For metal alloys and non-metals, a low thermal expansion coefficient generally favours mechanical strength. Rapid cooling and heating cycles, resulting in successive expansion and contraction as well as thermal shock, are most often the cause of element failure. Methods of element attachments and support, therefore, play an important role in the mechanical strength of the element system and their service life.

1.5. Furnace Environment:

The heating element material must withstand the corrosive nature of emanations from heat treated materials and/or of the ambient atmosphere in the furnace (air, different gases, molten material or vapours). Resistances used in vacuum must not evaporate at maximum operating temperature.

Generally, most types of heating elements form a protective (oxide) surface film during the first few hours of operation. This film allows the use of the element in different atmospheres. However, the recommended maximum operating temperatures, in a given atmosphere, are often lower than the maximum operating temperature in air.

1.6. Service Life:

The service life of an element depends on many intrinsic properties and operating factors.

Among the most important intrinsic properties of elements that allow for longer service life are: high softening and melting temperatures; relatively high resistivity; low, positive and constant temperature coefficient of resistivity; low thermal expansion coefficient; high mechanical strength; and high resistance to corrosion.

Operating conditions that could significantly reduce the service life of elements are: operating above the softening point of element; discontinuous operations (frequent cooling to ambient temperatures); mechanical defects or damage of the element or support system; careless handling/installation; and corrosive atmospheres.

It is, of course, very difficult to find a single material that satisfies all the requirements for long service life, but several types of elements are very close to meeting most industrial requirements.

1.7. Cost:

In simple terms, the cost of an element must be optimized against its service life, productivity and end product demand and value.

The average service life of an element under actual operating conditions should be accurately estimated from actual operating data in a plant, laboratory simulation tests or manufacturer data. Productivity for a given type of element in a furnace will depend on its power density, load properties, furnace utilization schedules and electricity rate structure. Market demand and value of the product could play a significant role in selecting the heating element to be used. Therefore, a thorough market analysis of the end product should be available.

In addition to the factors discussed above, other parameters must also be considered in the selection of heating elements: electrical power requirements, power supply type, supply voltage, type of regulation, heating chamber volume, volume available to house heating elements, element form/shape, ease of elements replacement, insulation and type of heating process. A compromise between all the factors mentioned must be made before selecting the most appropriate heating element.

2. HEAT CONTROL

One of the main advantages of electric resistance furnaces is the accuracy of controlling its temperature. Temperature stability and uniformity inside a kiln depends, among other factors, on its regulation. This is usually accomplished by controlling the electric power and the temperature of both the load and the heating elements.

2.1. Control Systems:

A control system consists of three basic components: temperature sensor(s) for measuring product, furnace and/or element temperatures; a comparator which compares the temperature measurements to a reference or set point value; and a power control device which varies the electrical energy supplied to the elements and therefore the heat energy produced. Different types of control systems currently exist. They can be classified as either discontinuous or continuous regulation.

2.2. Discontinuous Control:

Discontinuous or 'on-off' regulated furnaces are most common. In simple terms, heat control in this case is achieved by means of a temperature probe located between the elements and the load. The comparator determines the temperature difference between the probe reading and the set point and accordingly regulates the power supply through a relay which cuts off or applies electrical power to the heating elements. Figure A1 shows an example of an 'on-off' control system utilizing an electromechanical contactor (switch). In this case the heating elements are constantly supplied with maximum voltage during temperature rise. Once the maximum operating temperature (or set point) is reached, the control system periodically switches the power supply on and off such that the temperature of the elements follows a sawtooth pattern with a period T as shown in Figure A2. The average temperature of the elements is, therefore, less than their maximum operating temperature. This will result in limiting the maximum power density attained.

In many systems an element temperature-limiting device is incorporated in the control system, as shown in Figure A1. In these cases, the average maximum temperature is higher than that of the control system that does not feature the element temperature sensor, as indicated in the upper sawtooth curve of Figure A2. Because of the thermal inertia of the sensor, the maximum temperature limit is usually

exceeded. This will result in higher power densities, but at the expense of the service life of both the electromechanical relay device and the heating elements.

2.3. Continuous/PID Control:

Electric resistance furnaces using continuous control systems are not very common in industrial applications; yet, furnaces regulated by these systems appear to have significant advantages over furnaces with discontinuous controls.

Continuous control systems allow the electrical power supplied to the heating elements to vary from 0 to 100% of its maximum value. In general, continuous controls are Proportional, Integral and Differential (PID) systems:

- **proportional** as the power applied to the elements, near the set point and within a proportionality band, increases proportionally with the difference in temperature between the set point and the load;

- **integral** since corrective power is applied as a function of the integral of the temperature difference in a given time (ie, $\int \Delta T.dt$). This usually occurs when the proportionality band cannot be narrow and the temperature difference between the set point and the load is high;

- **differential** because temperature corrections are also a function of the derivative of the temperature difference in time. If the proportionality band is very narrow, temperature oscillations can occur. The differential action limits these oscillations and enables the final temperature to be reached more rapidly.

Regulation using thyristor devices are particularly suited to PID control systems. By placing thyristors in the power supply circuit of the elements, the current is regulated as a function of the temperature difference, its integral and/or its differential. The fast response of the thyristors permits a continuous modulation of the power applied to the resistance elements thus giving smooth heating curves as shown in Figure A3.

3. HEAT TRANSFER

In general, heat transfer in resistance furnaces obey three standard thermal laws: conduction, convection and radiation. Conductive heat transfer plays a small role in heat transfer between the elements and the object. However, energy transfer inside the charge and thermal losses through the furnace walls occur mainly by conduction mechanisms. Heating by convection, in most practical heating furnaces, occurs simultaneously with radiation heating up to 750°C. At higher temperatures, heat transfer between the resistance elements and the charge is predominantly radiative (Figure A4). The emphasis of this study will therefore be on conduction and radiation heat transfer.

3.1. Thermal Conduction:

Thermal conduction is the propagation of heat in a body or several contiguous bodies without the movement of the medium. It occurs mainly in a solid or between solids in contact when there is a temperature gradient. The (vector) relationship between heat flux (Φ) and temperature gradient (dT/dx), for a one-dimensional medium, is given by:

$$d\Phi/dS = - \lambda \, dT/dx \qquad [A7]$$

where S is the surface area where heat transfer occurs, and
λ is the thermal conductivity of the medium.

The negative sign in equation [A7] indicates that the heat flow is in the direction of temperature decrease, ie, from warm to cool.

In practical/industrial furnaces, heat transfer and loss through the walls occur mainly by thermal conduction. Therefore, furnace insulating materials should have a low thermal conductivity value that will minimize the heat loss across the walls (equation [A7]). The insulating walls of high temperature furnaces are usually constructed of layers of different materials, each having a thickness x_i and serving a specific purpose such as thermal insulation, corrosion resistance or mechanical support. If the composite walls are plane, the penetrating heat flux is given by:

$$\Phi = \frac{T_1 - T_{e+1}}{\Sigma x_i / \lambda_i S} \qquad [A8]$$

For a composite cylindrical wall, with each cylinder having an inner radius of r_i,

$$\Phi = \frac{T_1 - T_{e+1}}{R} \qquad [A9]$$

where $R = \frac{\Sigma \ln(r_{i+1}/r_i)}{2\pi \lambda_i}$

For furnaces with more complex forms, conduction heat transfer is determined from the fundamental equation of heat conduction. Equations [A8] and [A9], however, provide accurate analysis for most practical furnaces. These equations ([A7] - [A9]) should also be used to evaluate the energy and time requirements for heating the load (equation [A4]).

3.2. Convective Heat Transfer:

Convection is characteristic of heat propagation in a gas or liquid, where the molecules are in motion (therefore, in a vacuum, convective heat transfer does not apply). Heat transfer is improved as the fluid (gas or liquid) agitation increases. Two convective heat transfer methods usually apply in furnace heating: natural convection and forced convection. In the first method, the temperature differences within the furnace move the internal fluid and heat is transferred from the hot regions (the elements) to the colder ones (the load). Forced convection occurs as a result of mechanical mixing or blowing of the fluid in the furnace. This will result in faster heating and more uniform heat distribution. Since this study is concerned only with high-temperature furnaces, convection heating will not be analyzed in any further detail.

3.3. Radiation Heat Transfer:

Heat transfer by radiation occurs as a result of a temperature difference between two bodies separated by a space permeable to the radiation. Thermal radiation is an electromagnetic phenomenon which obeys the Stefan-Boltzman law:

$$\Phi = \varepsilon F \sigma S (T_1^4 - T_2^4) \qquad [A10]$$

where Φ is the thermal flux exchanged between the resistances and the load,
T_1 and T_2 are the resistance and load (absolute) surface temperatures,
S is the area of emitting surface,
ε is a coefficient accounting for the emissivities of the resistances, the load and insulation,

F is a form factor accounting for number of elements and their position as well as flux reflections from furnace walls,
σ is the Stefan-Boltzman constant = 5.73×10^{-8} W/m².K⁴.

The quantity ε . F, in equation [A10], is a complex parameter that takes into account the reflected flux from the furnace walls, the position of the element's surface(s) relative to the load's surface(s), the radiating and absorbing areas, and the emissivities of the walls and the load. For simplicity, this quantity could be defined as a global form factor, F_G, accounting only for the emissivities of the furnace contents ε_1, and its walls ε_2, as well as the surface area of the furnace contents A_1 and of the walls A_2/12/:

$$F_G = \frac{A_1}{1/\varepsilon_1 + A_1/A_2\ (1/\varepsilon_2 - 1)} \qquad [A11]$$

For most practical furnaces, the value of F_G is in the range 0.2 to 0.5 (maximum F_G value is 1.0). This suggests that improvements in the specific power produced by the elements are possible.

If all the electrical power applied to the elements is dissipated as thermal flux, then

$$\Phi = V^2/R = W = Q_T/t \qquad [A12]$$

This relation will provide the maximum temperature to be reached by a given type and size of resistance elements.

4. HEAT ABSORPTION

The heat energy emitted by the elements is mostly absorbed by the load material and the walls of the furnace. Thermal losses account for the balance of the energy emitted.

4.1. Heat Absorption By The Load:

For the material to be heated, the amount of (thermal) energy (Q_C) required to heat it to a final temperature T_2, is determined from the sum of the energy (Q_R) required to raise its temperature from an initial temperature T_1 to the final temperature T_2 and the latent heat(s) (Q_L) required if there is a change of state in the material (or parts thereof), ie,

$$Q_C = Q_R + Q_L \qquad [A13]$$

with $$Q_R = M\ C_P\ (T_2 - T_1) \qquad [A14]$$

and $$Q_L = M_L\ L \qquad [A15]$$

where M is the mass of the load
C_P its heat capacity
M_L is the (partial or total) mass of the load undergoing change of state during heating
L is the latent heat of change of state.

The knowledge of the required heating period, estimated from the thermal conductivity equation [A7], and an estimate of the quantities Q_s and Q_L (and hence the knowledge of Q_C) are necessary for the determination of the furnace's power requirements (equation [A4]).

4.2. Heat Absorption By Furnace Walls:

The heat absorbed by the furnace walls is either stored in the walls, dissipated through them and/or re-emitted back (and absorbed by the load or the other walls). The amount of absorbed energy is determined from the thermal capacity and temperature profile of the wall constituents. The stored energy maintains the heat flow to the load and enhances its temperature uniformity. Furnaces with high thermal mass walls will absorb and store more energy than furnaces with low thermal mass walls. For furnaces operating continuously for long periods of time (weeks), the high thermal mass will have a small effect on the energy efficiency of the furnaces. On the other hand, for intermittently or discontinuously operating furnaces, the large amount of stored energy will be completely or partially lost during cooling periods. In this case, energy efficiency is low and improvements are required.

Current trends in furnace technology are directed to using low thermal mass insulation. Fibre insulation is gradually replacing the traditional brick insulation/refractory. The use of this newer type of insulation resulted in significant reduction in heat loss and energy accumulation in the insulation. The net result is increased energy efficiency of all types of furnaces.

4.3. Heating Cycle:

Based on the analysis of energy requirements for both load and furnace walls, the heating cycle for a particular process and product can be estimated. Other important factors that are considered in determining the heating cycle for a product/process are the available furnace (heating) capacity, maximum power density of heating elements, size of load, its intrinsic properties (eg. thermal shock resistance and phase transformations), evaporation of gases, throughput requirements, and number of operating shifts per day.

The type and capacity of a furnace, however, could be dictated by the type and size of the load and its heating cycle requirements. With present-day technology, almost any reasonable requirement for a new furnace can be met. On the other hand, difficulties might be encountered in modifying existing furnaces to meet required changes in heating cycle to accommodate a different load, an enhanced production rate or to improve its energy efficiency. Also, changes in the properties of the load material, in some cases, might be required to be compatible with faster and/or more efficient heating cycles.

5. HEAT LOSSES

Reduction in energy efficiency of a furnace is primarily caused by thermal losses. These losses occur as a result of thermal conduction through the walls, losses through doors, cracks or slots within the insulation, heat absorbed by support furniture, losses through volatile products/vapours, and losses due to cooling of the furnace.

With the development of fibrous insulating refractories and the careful design of the furnace insulation and doors, furnace efficiencies can be significantly improved. Refractory bricks were the most common lining for high temperature furnaces. Because of their high density and thermal conductivity (and heat capacity), high temperature furnaces consumed significant amounts of energy. Fibrous insulation/refractory, on the other hand, have very low density and thermal conductivity values. Other

advantages of the fibre insulation are the fast heating and cooling cycles and better thermal control. Table AIII compares the properties of insulating/refractory bricks to several fibrous insulations currently available. A compilation of the thermal conductivity data, as a function of temperature, for various types of insulation materials are presented in Figure A5. Energy efficiency improvements ranging from 30 to 80% have been reported when brick refractory was replaced by fibre insulation/13,14/. Figure 6 shows two examples of the significant energy savings achieved by replacing traditional refractories and insulation by fibre insulation.

In selecting the insulating material of a furnace, non-thermal properties must also be considered and evaluated. Some of the relevant insulation properties are:

mechanical properties: high mechanical strength at elevated temperatures, good thermal shock resistance and low shrinkage;

chemical properties: resistant to corrosive atmospheres and must not produce gases that are corrosive to the elements and/or the load;

electrical: high electrical resistance at all temperatures;

form: could be easily shaped, cut and/or formed in various dimensions and configurations;

cost: should be as low as possible for fast payback periods.

TABLE AIII
TYPES AND PROPERTIES OF COMMON INSULATING MATERIALS

TYPE	COMPOSITION	MELTING POINT °C	THERMAL CONDUCTIVITY At 1000°C W/m°C	DENSITY g/cm³
High Density Brick	Oxides of: Al, Si Fe, Ca & Na	1915	2.9	2.9
Insulating Fire-Brick	Al_2O_3, SiO_2, CaO, TiO_2	1800	0.5	0.85
High Alumina "Plastics"	Al_2O_3	2000	0.86	1.0
Cera Form Refractory Fibre	Al_2O_3-SiO_2	1820	0.22	0.35
Duraboard 3000 Fiberfrax	Al_2O_3-SiO_2	1870	0.2	0.2
Microtherm	65% SiO_2-32% TiO_2 Al_2O_3	1100	0.04	0.33
Zircar ZYFB 3 Fibre	92% ZrO_2-8%Y_2O_3	2400	0.1	0.48
SALI Fibre Boards	80%Al_2O_3-20%SiO_2	2000	0.25	0.48

6. DISCUSSIONS WITH MANUFACTURERS

The **potential for efficiency improvements in electric resistance furnaces** was discussed with several furnace and insulation manufacturers. In order to have uniform, well-balanced data, specific questions were asked to each of the manufacturers. These questions were related to the following points:

- company information;
- type of electric resistance furnaces or insulation manufactured;
- industrial sectors in which furnaces are used (applications);
- any type of furnaces that are more efficient than others;
- methods applied for improving efficiency of furnaces:

  for already installed units;
  for future units;
  (elements; insulation; design; power control; other)

- R&D projects that could result/assist in improving furnace efficiency?

The companies that participated in the discussion were:

Furnace Manufacturers:

Centorr Furnaces, Suncook, New Hampshire.
Synergetic, Oakville, Ontario.
Harper Furnaces and Kilns, Lancaster, New York.
Ordan Thermal Products, Unionville, Ontario.

Insulation Manufacturers:

Ferro Corporation, Cleveland, Ohio.
Zircar Products, Florida, New York.
Ceramic Refractory Group, Transfer, Pennsylvania.
Cerefco Inc., Guelph, Ontario.

In addition to the information provided by these manufacturers, technical data for a variety of resistance elements, insulating materials and coatings were collected from various sources including expositions and other manufacturers.

The results of the discussions and data analysis could be summarized in the following points:

- Electrical energy is still more expensive than energy derived from fossil fuel, in particular natural gas.
- Natural gas furnaces are still more common than electric ones.
- Sales of electric resistance furnaces are strong and steady.
- Fast heating is the most significant advantage of electric resistance heating furnaces. 'Fast-fire' gas furnaces are now available.
- Except for the electronic industry, environmental concerns are not critical issues in the use of gas furnaces.
- Most common applications: melting and holding of metals, annealing and melting of glass, electronic materials and some sanitary ware.
- Electrical efficiency of electric resistance furnaces is approaching 100%.
- An excellent variety of elements is available to meet all heating requirements.
- Cost of elements is an important factor for installation. $MoSi_2$ elements are the most expensive type.
- Type of insulation is the most important parameter to affect thermal efficiency.
- Insulation linings must satisfy many criteria at minimum cost. Several types and layers are, therefore, used in a single furnace.
- Low thermal conductivity and thermal mass insulation are becoming increasingly popular in furnace construction.
- Main concerns for using low thermal mass insulation are their relatively high cost, non-uniform heating and low strength.
- Although superior insulating materials are currently available, their cost is almost prohibitive for most applications. At about $20 per square foot, most manufacturers shy away from them. Only manufacturers of high-value-added products could afford to use expensive insulation.
- Hot spots and non-uniform heating in furnaces using low thermal mass insulation arise as a result of the non-uniform distribution of elements within the furnace and the low thermal conductivity of the insulation lining. Such furnaces must be carefully designed with special attention given to the position of the elements relative to the load and its size.
- Low strength insulation is usually placed in locations where strength is not required.
- Lack of good element support is one of the furnace manufacturers concerns.
- Present furnace designs are satisfactory. Reducing the surface area of the heating chamber will minimize energy consumption.
- Structural stability of the insulation lining is a critical factor in furnace design and efficiency.
- Furnace rebuilding/retrofitting is usually undertaken by insulation and heating element manufacturers and not by furnace manufacturers.
- Mass of insulation shipments has been falling drastically in the past decade due to the increasing use of low mass insulation.
- High emissivity coatings are not common. In fact, most furnace manufacturers are not aware of their existence.
- Heat reflecting (aluminum) coatings, sprayed/painted on the inside surface of the furnace casing are occasionally used. These coatings have insignificant effects on furnace efficiency.
- An air gap between insulation layers will improve the average emissivity of the insulation since cooler surfaces of most refractory materials have higher emissivities than warmer surfaces.
- High emissivity coatings are expensive. As a result, furnace buyers/users seldom purchase these coatings.

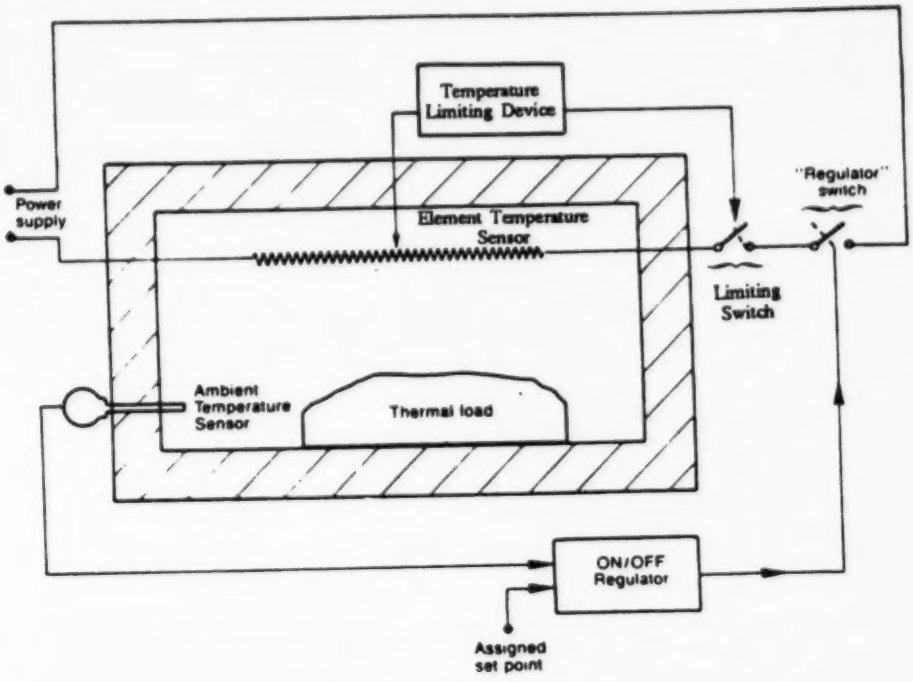


FIGURE A1

On/Off Control System Using Electromechanical Switch

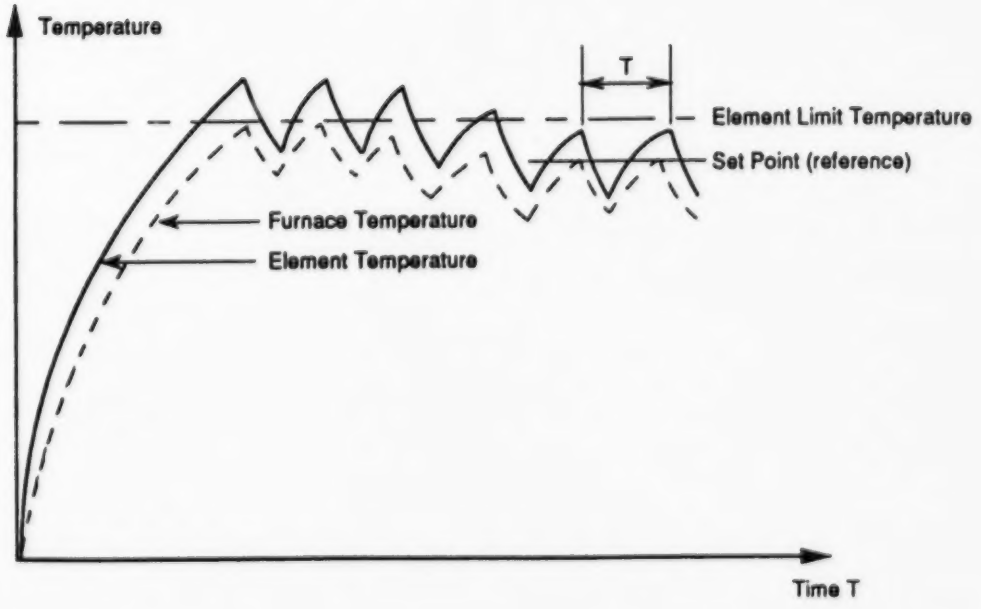


FIGURE A2

Temperature Profile In A Resistance Furnace With An On/Off Control

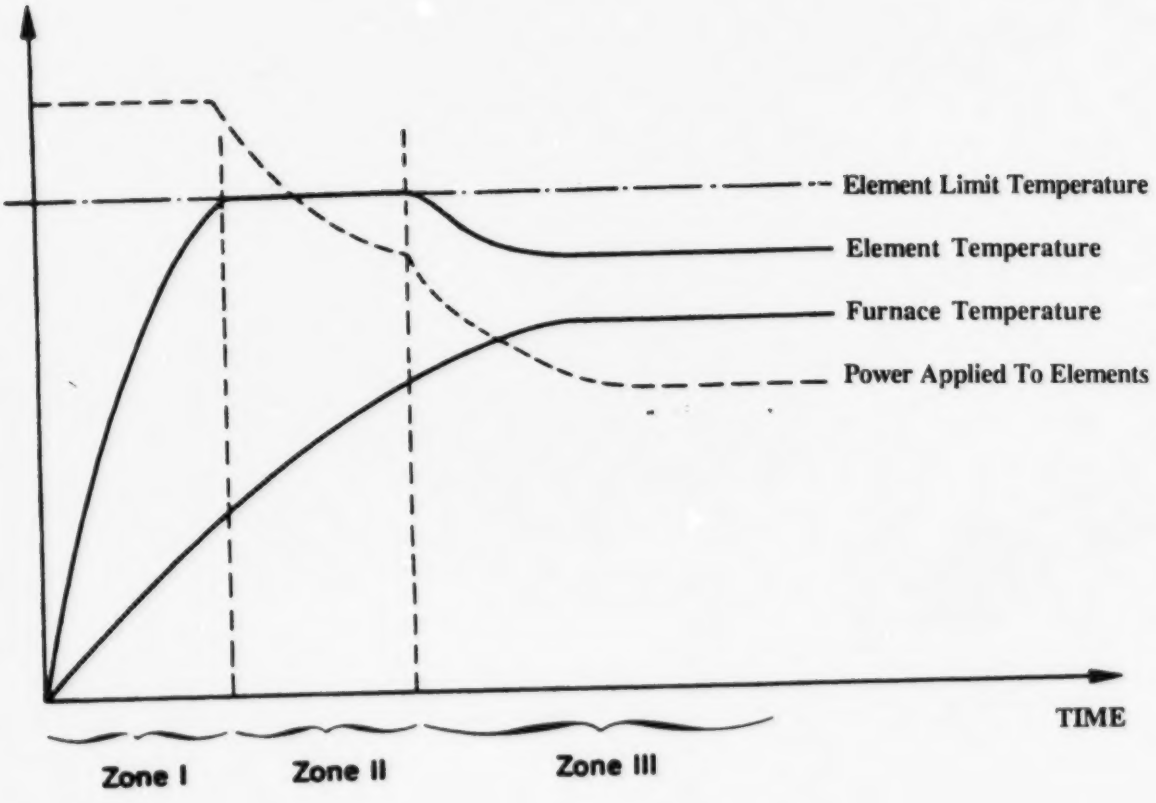


FIGURE A3

Heating Curve For A Furnace Using PID Thyristor Temperature Control

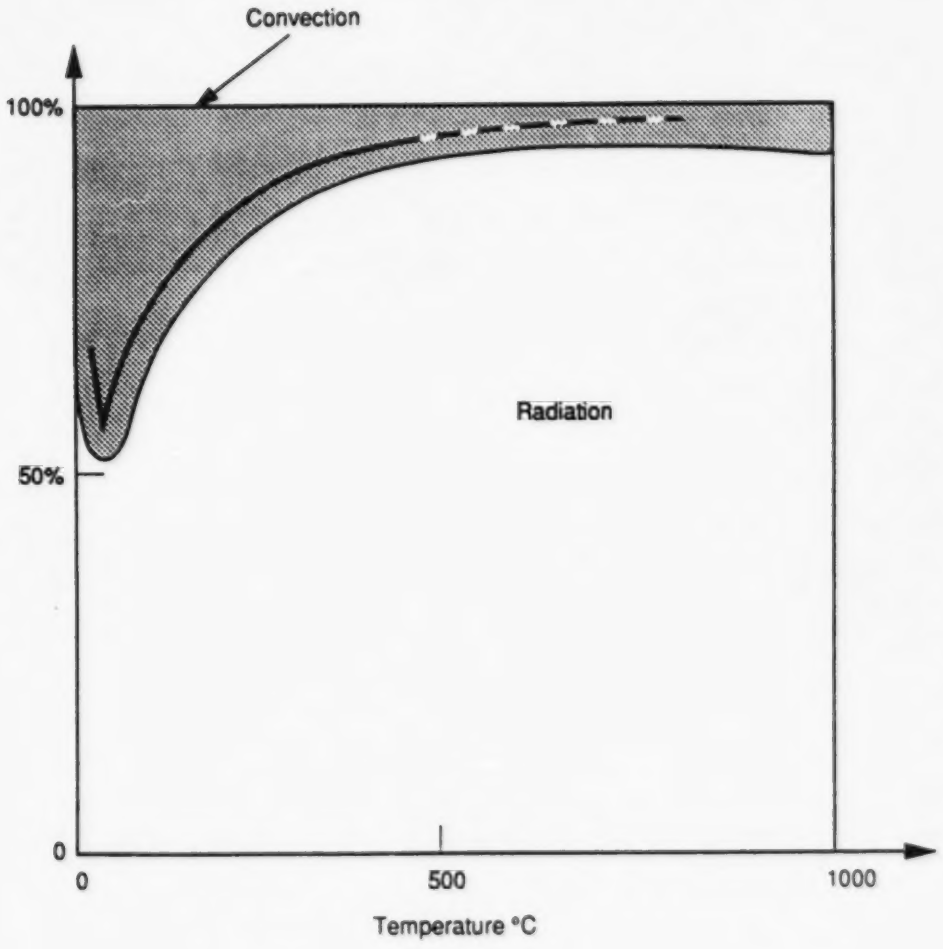


FIGURE A4

Radiation And Convection Heating In Furnaces

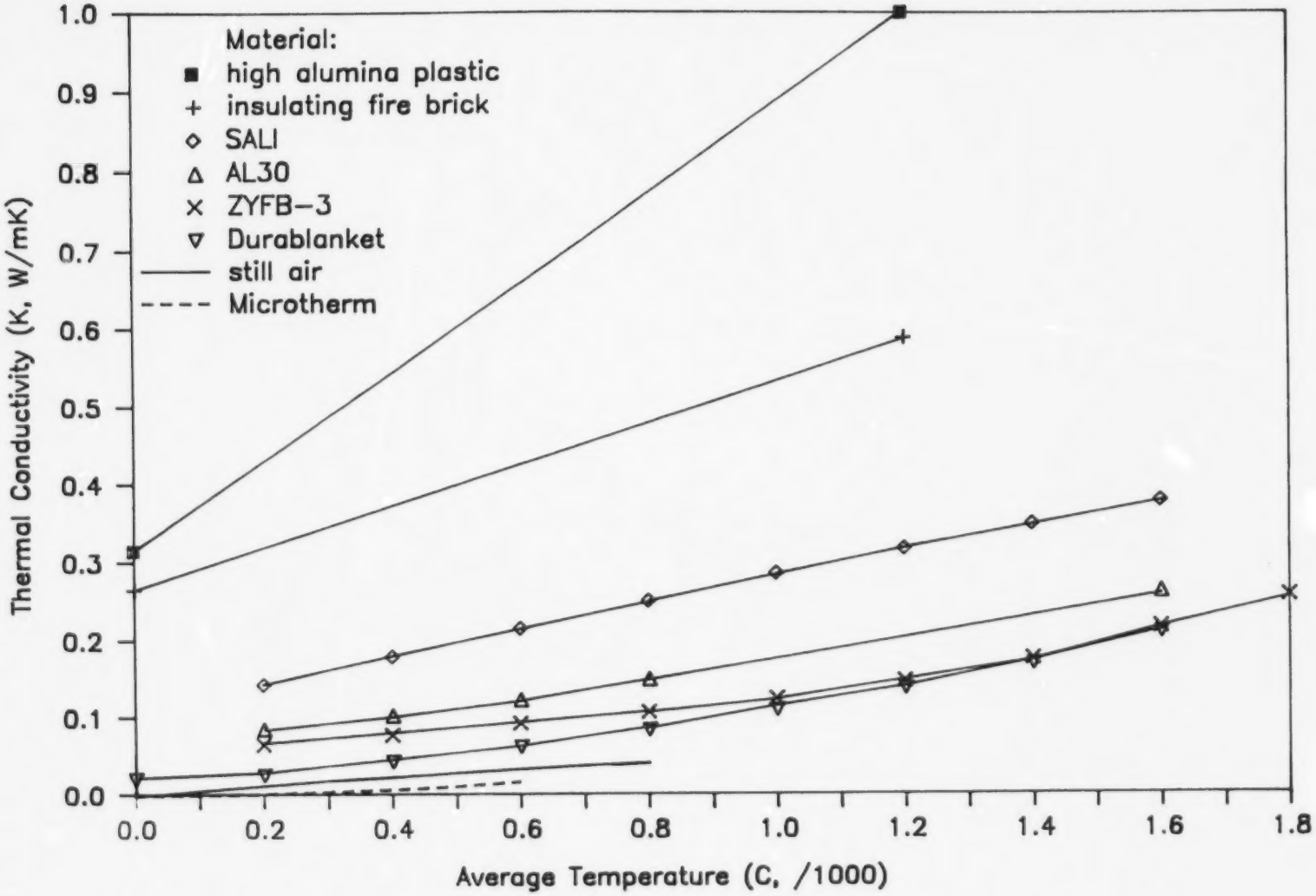
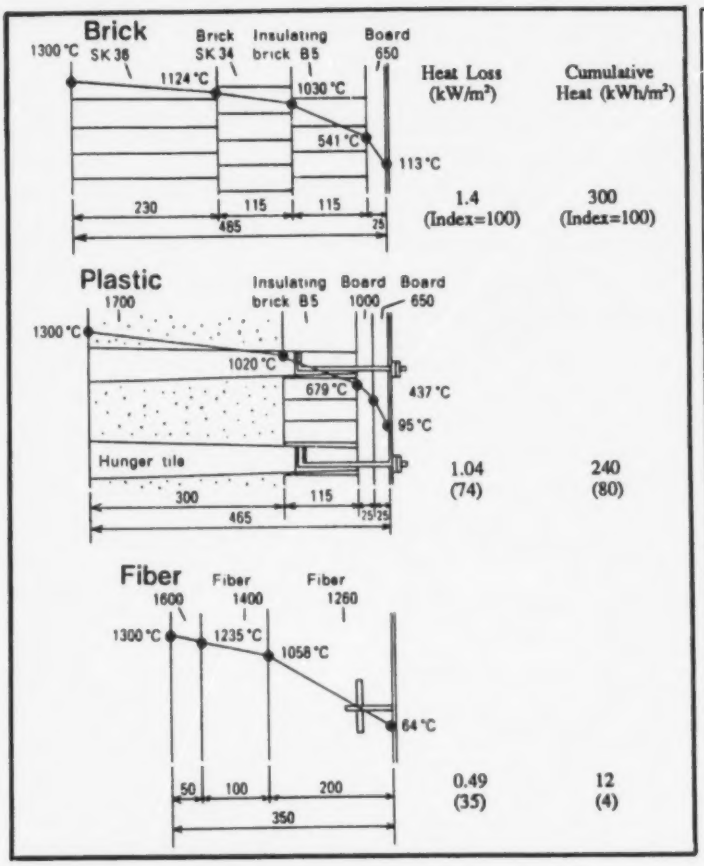
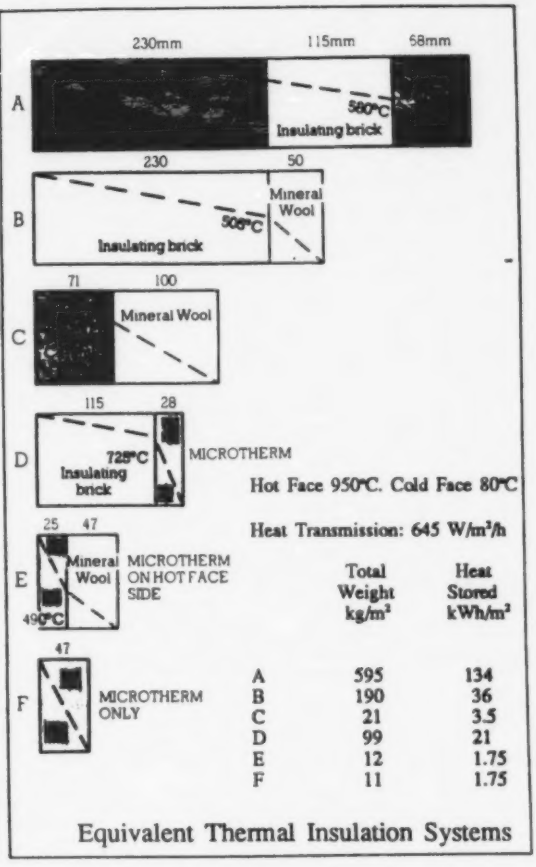


FIGURE A5

Thermal Conductivity For A Variety Of Insulating Materials



EXAMPLE A



EXAMPLE B

FIGURE A6

Examples Of Energy Savings Resulting From Replacing Traditional Insulation By Fiber Insulation